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TECHNOLOGY BRIEF

Solder

Joint

Rework

Simulation

Analysis

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Solder Joint Rework Simulation Analysis

by the
Electronics
Manufacturing
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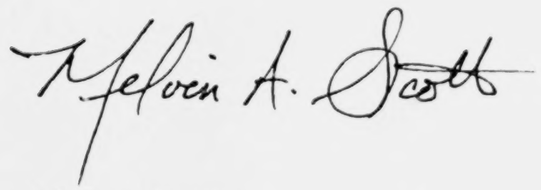
EMPF TB 0019

Foreword

This Brief is part of a series of Technology Briefs published by the Electronics Manufacturing Productivity Facility (EMPF). Describing research projects designed to further the understanding of manufacturing processes, this series provides a vehicle for technology transfer between government and the electronics manufacturing industry.

Established by the Navy as a research center for electronics manufacturing, our objective is to improve what has been called the "world's most complicated process"—the process of taking a weapon system from design through production. We work in close cooperation with industry to develop and demonstrate the high quality materials, processes, and process controls necessary to strengthen the Nation's electronics manufacturing base.

This Brief describes an EMPF study using the computer modeling technique of finite differencing analysis. This technique was used to identify thermal stress in the design of a circuit assembly. In a manufacturing environment, finite differencing analysis can increase product reliability.



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Contents

Section	Page
Executive Summary	
Introduction	1
Equipment Overview	1
Tests	1
Results and Conclusions	1
Equipment Overview	
Introduction	2
METCAL	2
SINDA Software	2
Tests	
Introduction	3
Procedure	3
Results	6
Conclusions	8
Bibliography	9

List of Appendixes

Appendix		Page
A	Color Thermal Profiles of Rework Process Simulation	11
B	Acronyms	39

List of Tables

Table		Page
1	Nodal Mesh Ranges and Representations	6
2	Thermal Properties Used in the SINDA Input Deck	6

List of Figures

Figure		Page
1	Nodal Mesh Cutaway View	3
2	Solder Joint Close-up	4
3	Solder Joint and Test Board Dimensions	4
4	Soldering Iron Tip Mesh	5
5	Numbered View of Solder joint Nodal Mesh	5
6	Top, Side, and Combination Views of Solder Joint	7
7	Tip Thermal Profile Nodal Mesh	7
8	Time/Temperature Relationship Showing Solder Behavior Under Thermal Load	8

Executive Summary

Introduction

It is theorized that the thermal characteristics of a solder joint during the rework process has a direct affect on the reliability of that joint. While the amount of time spent reworking a connection can easily be observed and quantified, it is difficult to determine the time required for solder joint reflow. Infrared thermometry can be used to determine the temperature of the joint, but further information cannot be obtained by this method. Computer modeling through finite differencing analysis, however, is a technique that is capable of providing a greater quantity of valuable information about solder joint behavior during rework.

A finite differencing analysis study that simulated the rework process of a solder joint was performed at the Electronics Manufacturing Productivity Facility (EMPF). This summary provides an overview of the equipment, methodology, and test results.

Equipment Overview

This section describes the soldering system and the software package used in this study.

Soldering System

The soldering system used as a heat source model for this study included a self-regulating skin effect heater. The heater characteristics include:

a. A laminar all metal structure containing a ferromagnetic alloy.

b. A Curie temperature at which the ferromagnetic heater material loses its ferromagnetism and becomes paramagnetic.

c. A constant current Radio Frequency (RF) power supply.

d. The phenomenon of the skin effect of current within conductors. . .

Analysis Software

A general thermal analyzer software system was used in this study. The system is designed to solve lumped parameter representations of physical problems governed by diffusion-type equations. The software system can be used for a variety of simulation applications and requires an input deck for specific applications. The system is flexible and accommodates user-written FORTRAN subroutines. The system can be run on a mainframe computer. A personal computer (PC) version of the software package also is available for use on any IBM PC or compatible model.

Tests

Thermal overstress can significantly damage a printed circuit board (PCB), especially during rework. An expensive board could be destroyed simply because the soldering iron remained on a solder joint a second too long. This study was conducted in an effort to quantify the time required for solder joint reflow, thereby reducing the chance of thermal overstress. Finite differencing analysis was used to model the solder joint and soldering iron tip.

Results and Conclusions

Node temperatures are output as a function of time by SINDA. By using a graphical FORTRAN program, color contours were used to display the results across a computer-generated nodal mesh of the solder joint and soldering iron. The project was successful in that the examination of internal solder joint details was made possible without altering the physical properties of the printed circuit assembly (PCA). Finite differencing analysis is a complex, yet extremely useful, thermal modeling tool. With it, engineers can determine the soldering iron temperature setting best suited for a given board design and greatly reduce the possibility of thermal overstress.

Introduction

This section describes the soldering system and software used in this study.

Soldering System

A self-regulating skin effect heater was used as a heat source model. Heater characteristics include a laminar all metal structure containing a ferromagnetic alloy, a Curie temperature, a constant current RF power supply, and the phenomenon of the skin effect within conductors.

The alternating current (AC) skin effect defines the distribution of current along the cross-section of the conductor. The current distribution changes along with changes in the frequency of the AC, the magnetic permeability of the conductor, and the bulk resistivity of the current-carrying material. ACs are predisposed to flow along the surface of a conductor. The depth from the surface in which the current flows is referred to as the skin depth of current penetration.

The Curie effect describes the relationship between temperature and magnetic permeability in ferromagnetic materials. As the temperature of a ferromagnetic substance increases, it becomes more paramagnetic. The magnetic permeability decreases until the Curie point of the material is reached and the material becomes nonmagnetic.

The thermal power generated by the heater is directly related to changes in magnetic permeability. The self-regulating characteristic of the heater is based on the change in permeability. As the permeability decreases in relation to increasing temperatures, the skin depth of the current increases. The increase in skin depth causes the current path to shift from the thin, highly resistive ferromagnetic layer with a small conductive area to a thick, low resistance copper layer with a large conductive area. As a result of the increase in area, the resistance in the heater decreases, causing a decrease in thermal power. The power delivered is based on the product of the square of the current and resistance. As the power decreases, the rate of temperature increase slows and temperature control begins. If the current is kept constant, the power delivered varies with changes in resistance. Because the permeability change is quite sharp as the heater temperature approaches its Curie point, the power delivery can be substantial relative to a small temperature decrease.

The following equations were used to relate power generated versus temperature at a given location on the soldering iron tip.

$$P = -1/t \ln (T/K)$$

(tip temperature decreasing)

and

$$P = (K - T)/m$$

(tip temperature increasing)

where:

t and K are constants, T is the temperature at a given location, and m = slope.

Analysis Software

The software system used in this study is a general thermal analyzer designed to solve lumped parameter representations of physical problems governed by diffusion-type equations. The system accepts conductor-capacitor (C-C) network representations of thermal systems. Other problems that can be represented as C-C networks can be solved by the analyzer.

The software system comprises a preprocessor and a library. The preprocessor program accepts problems written in the system language and FORTRAN. Most commonly needed functions are performed by the library, which consists of prewritten FORTRAN subroutines. These subroutines reduce the programming effort, which might otherwise have been required to solve a given problem.

The software system can accept network description cards and other relevant values as input data as well as program-like logic statements and subroutine calls (library or user-supplied).

Equipment Overview

Introduction

Many process tests rely solely on experimental methods to obtain results. There are, however, elements of manual soldering that cannot be fully assessed in the laboratory because of time and expense factors. One such element is thermal overstress on solder joints. Caused by excessive dwell time on the connection, thermal overstress is of major concern during PCA rework because of the temperature sensitivity of electronic components. Since thermal overstress can significantly damage a board or component, the ability to quantify time required for solder joint reflow is an important manufacturing advantage. Finite differencing analysis provides that capability.

EMPF research involved the use of SINDA software to simulate the rework process of a solder joint. Simulation output was in the form of a time file with corresponding nodal temperatures. These temperatures were displayed with an EMPF designed FORTRAN program which utlized IBM Graphic Display Data Manager (GDDM) subroutines. Actual thermal characteristics of a soldering iron tip were used to construct the model.

Tests

Procedure

older joint, PCB, component lead, and soldering iron tip geometries were defined prior to finite differencing analysis, and a representative nodal mesh of these elements was constructed. Since both the soldering iron tip and the PCA are bilaterally symmetrical, only half of the solder joint, PCB, component lead, and soldering iron tip had to be modeled. This method of modeling saved compilation time and memory space, while making input deck alterations easier and faster. The resulting nodal mesh model is illustrated in Figure 1. The solder joint geometry is illustrated in the close-up view in Figure 2.

The overall dimensions of the solder joint nodal mesh, including the board, are 0.500 by 0.100 inch thick. The solder joint measures 0.075 inch across the board surface, 0.034 inch as it passes through the board, and 0.100 inch thick measured in cross section. The lead dimension is 0.020 inch in diameter, and the PCB measures 0.060 inch thick. All dimensions were derived from the standard EMPF test board (Figure 3).

The nodal mesh configuration is a semicircular pattern. Nodes were formed by making vertical radial cuts from the center of the copper lead. Vertical concentric circular cuts were also made, giving the mesh a dart board appearance when viewed from the top. A layering process completed the nodal mesh, thereby accurately duplicating solder joint geometry and its response to a thermal input.

Four PCB layers and 10 solder joint layers were the result of this configuration. There were 256 solder nodes, 152 nodes representing the component lead, and 320 PCB nodes. The volume of air surrounding the joint brought the total number of nodes to 729.

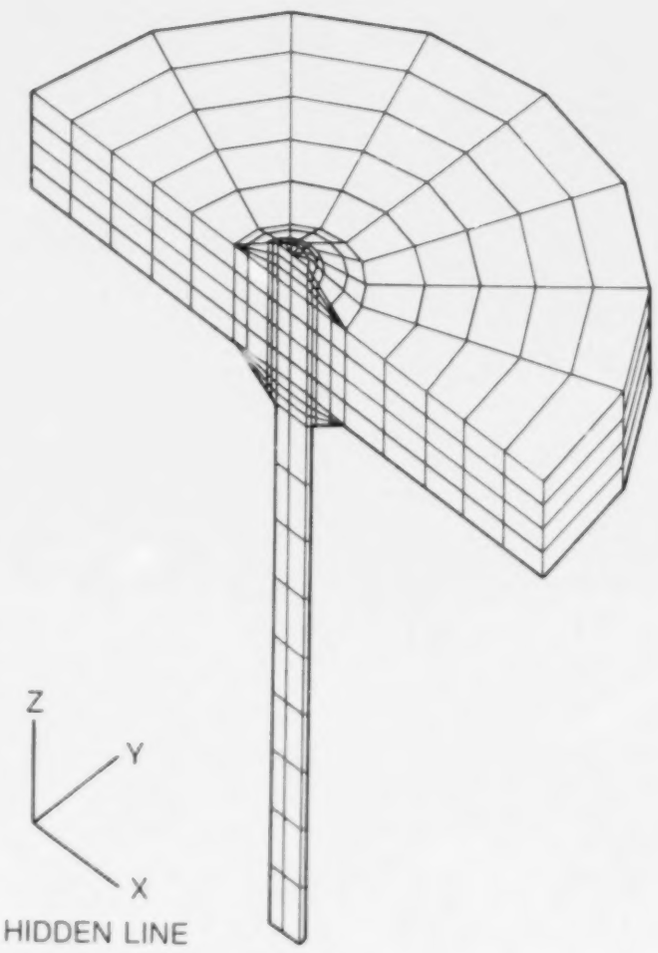

FIGURE 1. Nodal Mesh Cutaway View.

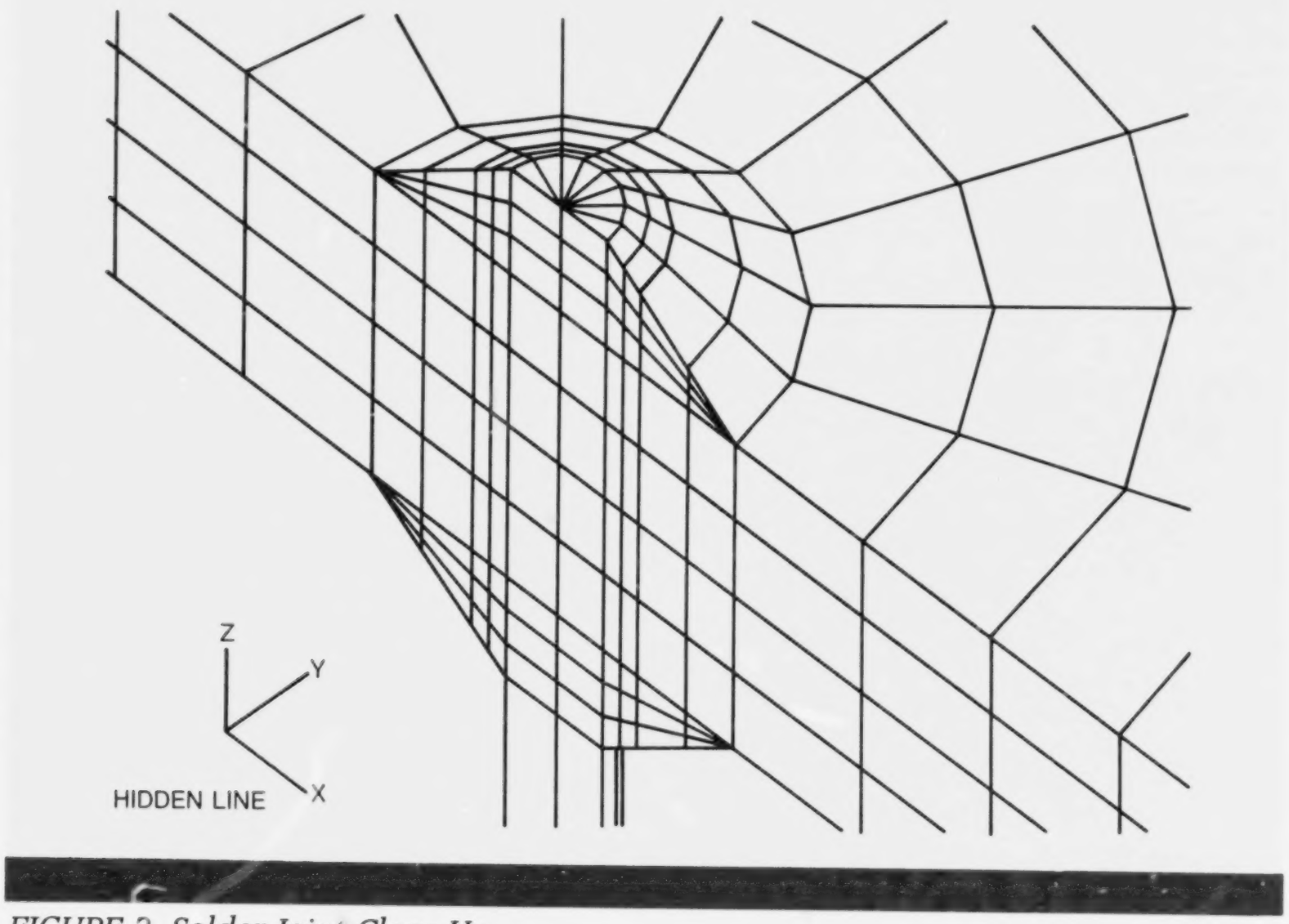

FIGURE 2. Solder Joint Close-Up.

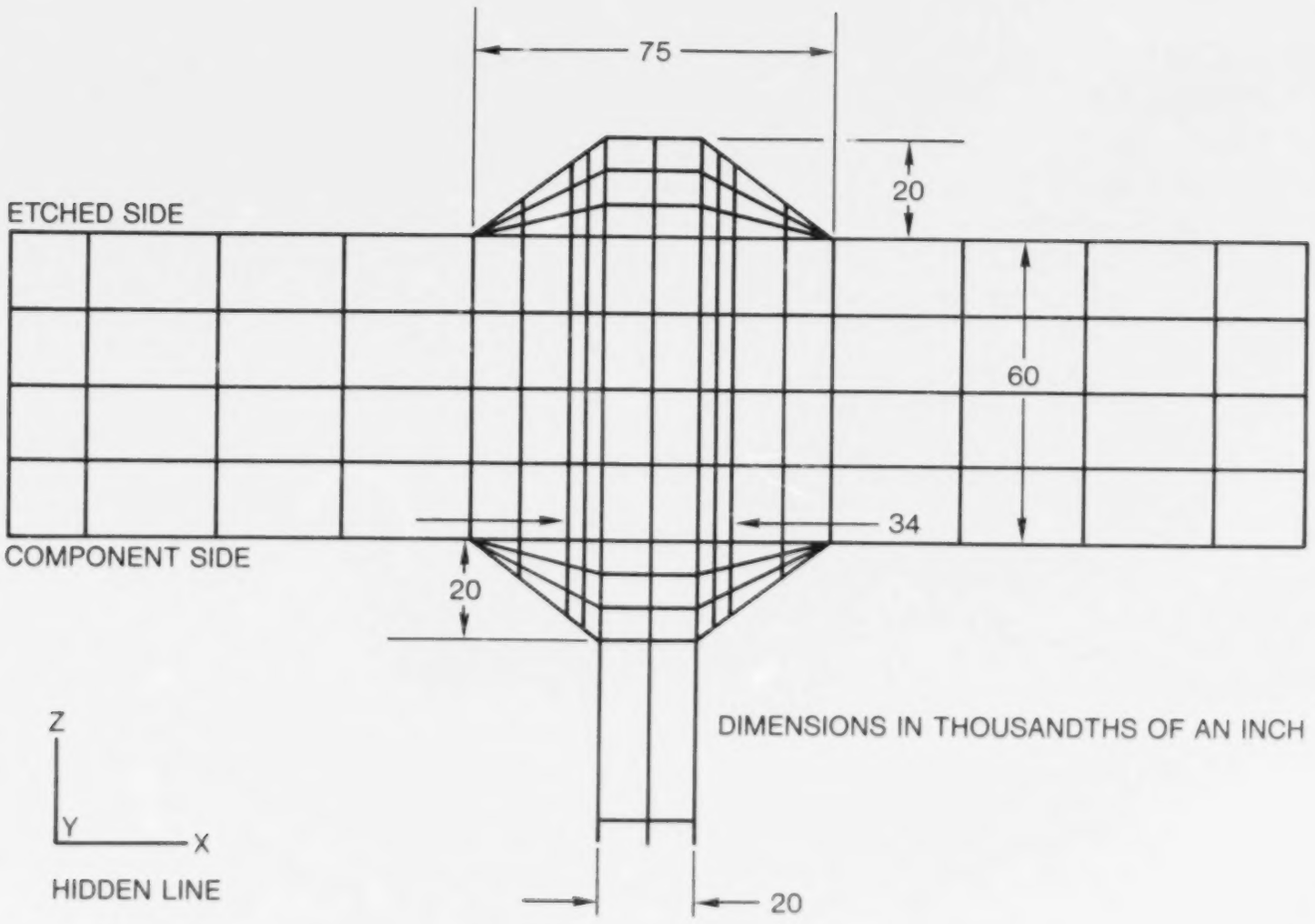

FIGURE 3. Solder Joint and Test Board Dimensions.

Another nodal mesh was generated to simulate the soldering iron tip. The tip is 0.500 inch long and 0.188 inch thick at the heating element, tapering to 0.014 inch at the end. Nodes were formed by vertically dividing the soldering iron tip into nine layers. Each of these layers was then horizontally divided into 10 sections, resulting in a mesh of 90 nodes. The soldering iron tip model is illustrated in Figure 4.

The complete SINDA input deck consisted of 819 nodes. Table 1 lists the node ranges and what they represent. Figure 5 depicts a reduced view of the solder joint nodal mesh with the node numbers inserted.

Tests

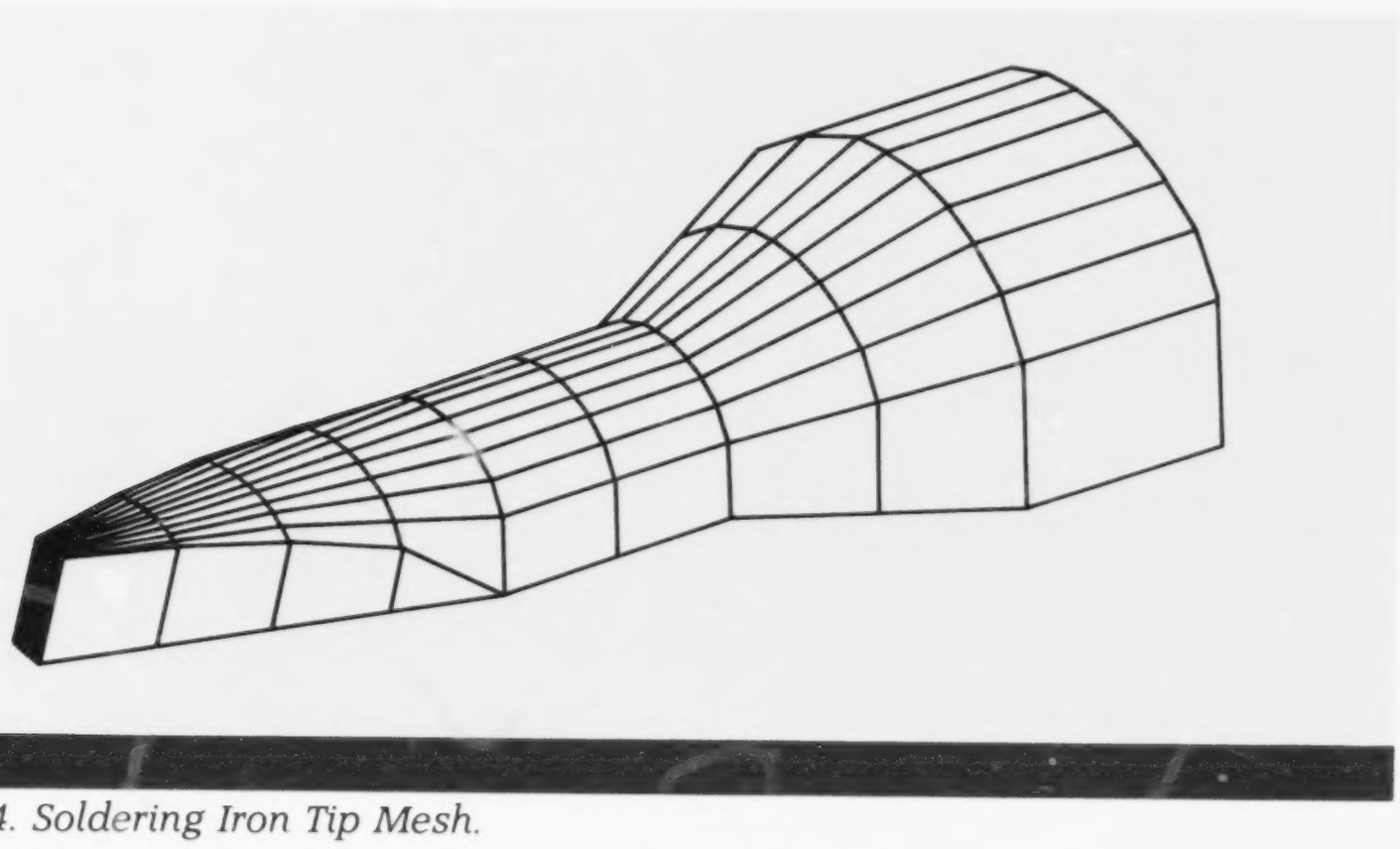

FIGURE 4. Soldering Iron Tip Mesh.

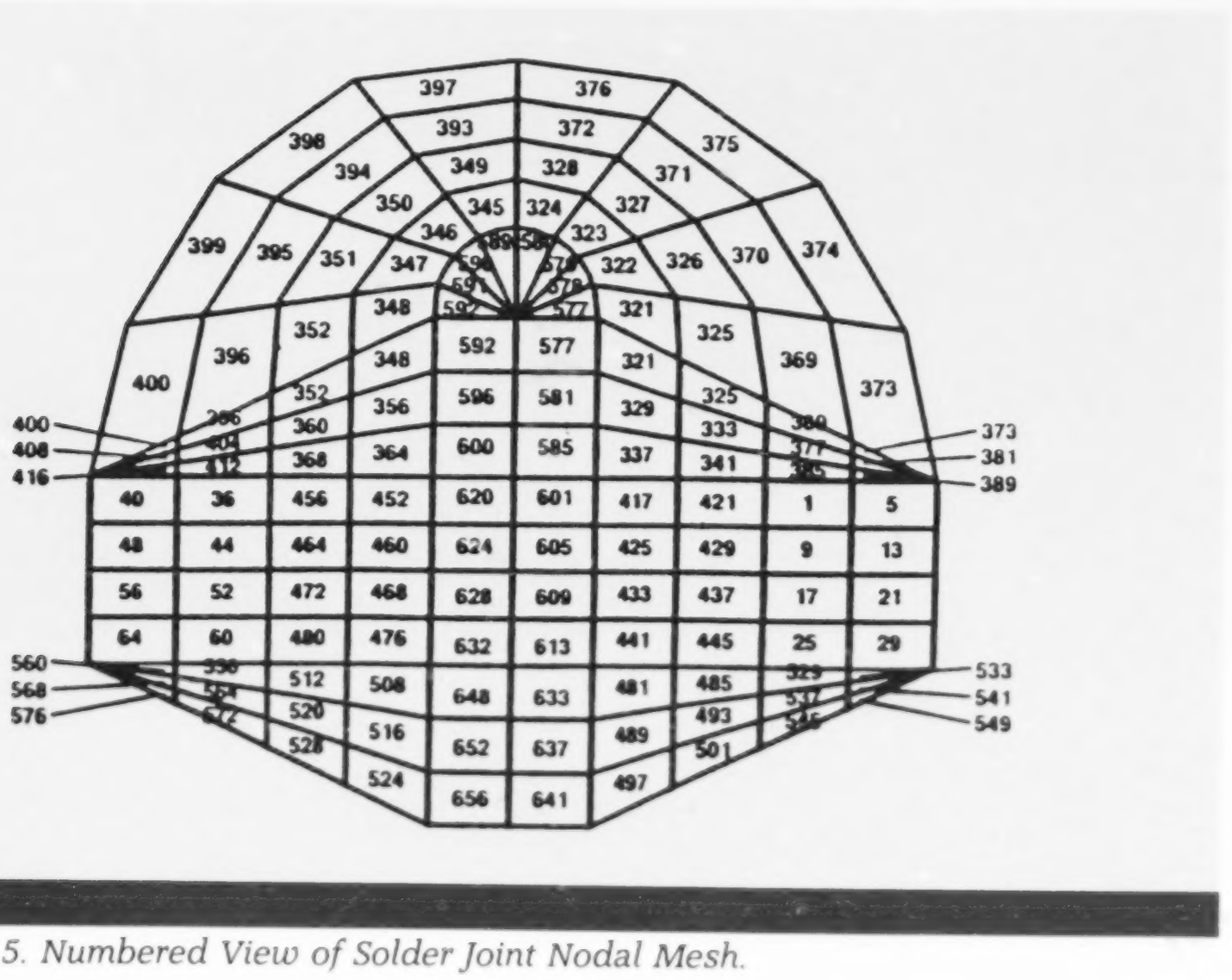

FIGURE 5. Numbered View of Solder Joint Nodal Mesh.

Node Range	Model Representation
1 to 320	Printed Circuit Board
321 to 576	Solder Joint
577 to 728	Component Lead
901 to 990	Soldering Iron Tip
1000	Surrounding Air

TABLE 1. Nodal Mesh Ranges and Representations.

Free convection cooling coefficient subroutines were used on the board, solder joint, lead, and soldering iron in order to make the convection coefficient temperature and orientation dependent. The soldering iron initial temperature profile was obtained using a separate model of the iron in conjunction with new subroutines and experimentally derived heater equations.

Materials used in the input deck were PCB fiberglass epoxy (FR4), copper in the component lead and soldering iron tip, 63 tin/37 lead solder, and air for the boundary node. Table 2 lists the material properties used in this simulation. The properties required by SINDA were thermal conductivity (k) in Btu-in-s-°F, and the product of the density times the specific heat (ρ X C_p) in Btu/in^3-°F.

The change in phase of solder that occurs at 361°F was also included. Heat of fusion, or the energy required to change solder from a solid to a liquid phase, was also included in the input deck. The heat of fusion value used in this nodel was 28 Btu/lb.

Results

SINDA produced a textual output of temperature as a function of time. This output format was acceptable for a small input deck, but too cumbersome for larger files. Therefore, a subroutine was written and added to the SINDA input deck to create a separate time and temperature output file for each output time step so that this data could be easily read by a FORTRAN program. A graphical FORTRAN program was written to read the numbers and convert them into colors. A colorized representation of both the PCA and soldering iron could then be called up on the computer screen. (See Appendix A for color thermal profiles of the solder joint and tip.) The resulting program utilized GDDM subroutines.

Material	Temperature, °F	Thermal Conductivity (k), (Btu/in-s-°F)	Density x Specific Heat (ρC_p) Btu/in^3/°F
Fiberglass Epoxy	0.0	0.2142E-05	0.1218E-01
	5000.0	0.2142E-05	0.1218E-01
Copper	0.0	0.5350E-02	0.2972E-01
	5000.0	0.5350E-02	0.2972E-01
Solder	0.0	—	0.1290E-01
	68.0	0.6607E-03	—
	158.0	0.6607E-03	—
	284.0	0.6271E-03	—
	360.9	—	0.1290E-01
	361.1	—	0.1780E-00
	464.0	0.3025E-03	—
	788.0	0.3920E-03	—
	5000.0	—	0.1780E-00
Air	32.0	3.2407E-07	1.1313E-05
	100.0	3.5648E-07	9.8843E-06
	200.0	4.0278E-07	8.3738E-06
	4000.0	—	2.0197E-06
	5000.0	4.0278E-07	—

TABLE 2. Thermal Properties Used in the SINDA Input Deck.

The tip and the solder joint were displayed separately because of their size differences and temperature variations. The solder joint appeared as a combination of the top and side views (Figure 6). Input deck materials, including solder, copper lead, and fiberglass epoxy board, are represented in the view. The tip thermal profile was illustrated in a similar manner (Figure 7).

A simplified relationship of temperature and time is shown in Figure 8. The curve represents how solder reacts under thermal load. Note that the maximum temperature of more than 600°F was reached quickly, while the minimum temperature reacted more slowly. The minimum temperature was also held constant between 0.975 and 1.075 seconds as the coolest node went through phase change.

Tests

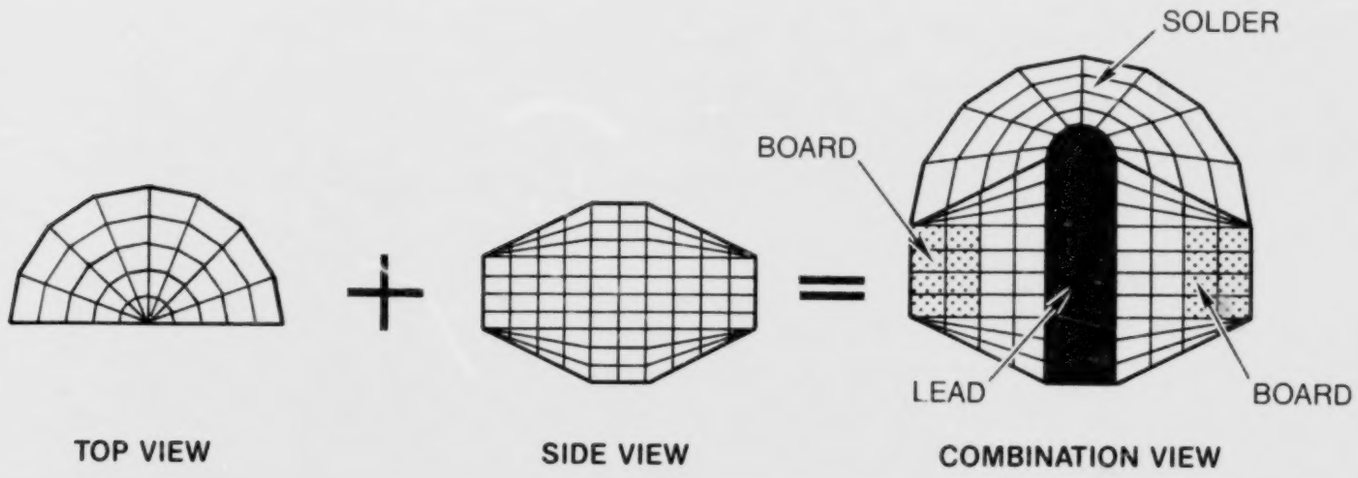

FIGURE 6. Top, Side, and Combination Views of Solder Joint.

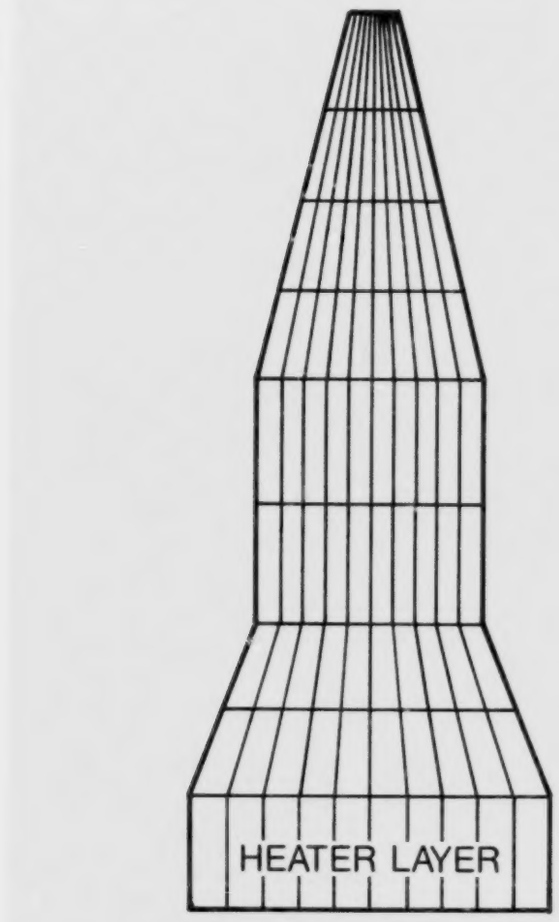

FIGURE 7. Tip Thermal Profile Nodal Mesh.

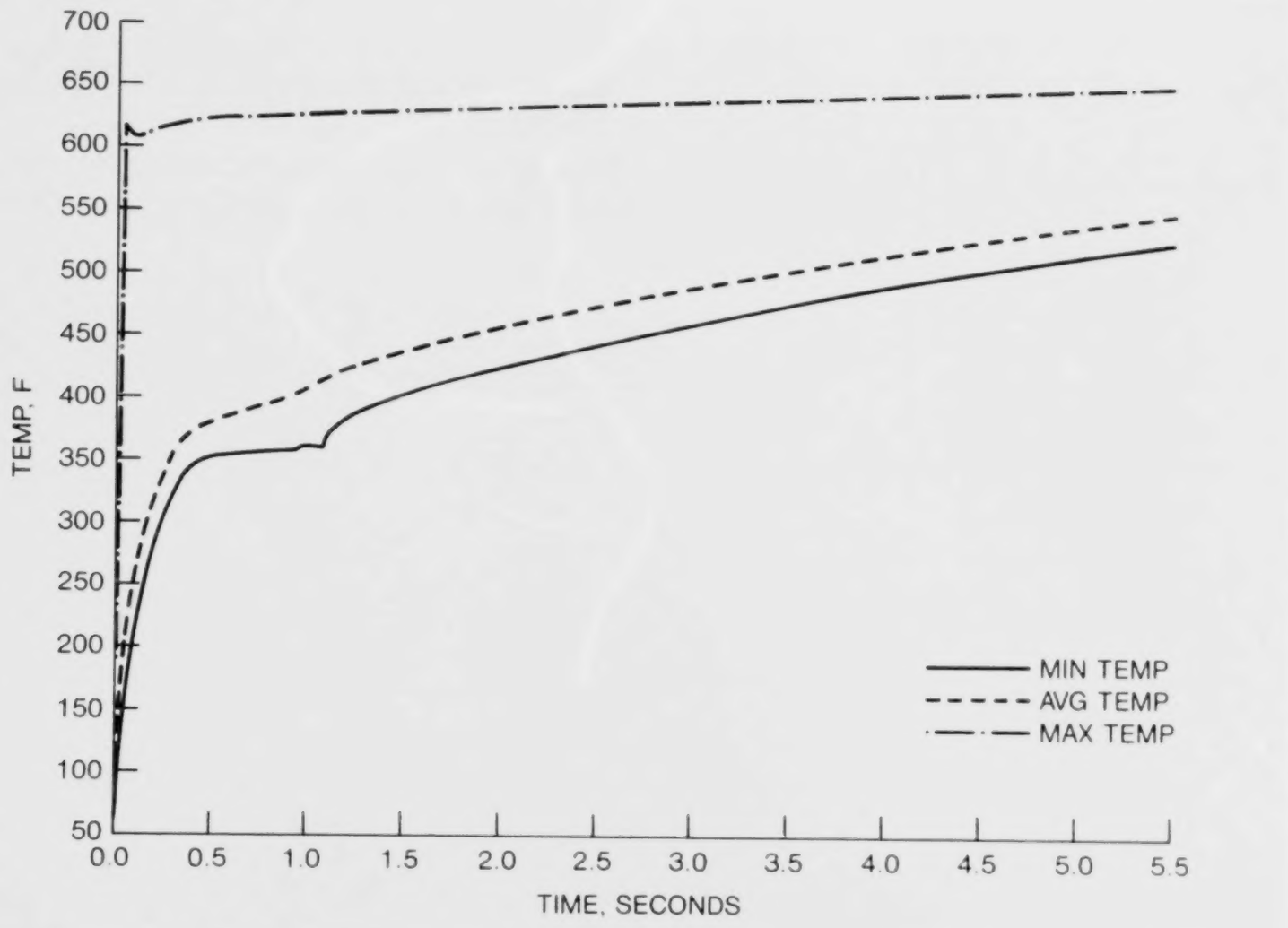

FIGURE 8. Time/Temperature Relationship Showing Solder Behavior Under Thermal Load.

Conclusions

This project demonstrated that finite differencing analysis is an invaluable tool for isolating variable solder joint elements. Specifically, it was possible to examine internal details of the solder joint and soldering iron tip without changing their physical properties. An inspection of this nature would be impossible in a laboratory environment.

Finite differencing analysis is also flexible in that material properties such as solder ratios and lead materials can be manipulated with little effort. Hence, a wide variety of materials may be inexpensively analyzed, enabling users to determine which combination best meets their needs. Finally, the analysis environment can be easily changed by altering the initial tip thermal profile. Such a modification is useful in determining a temperature setting best suited for a given board design, thereby greatly reducing the possibility of thermal overstress.

Electronics Manufacturing Productivity Facility. *Conductive Point-to-Point Soldering.* HB 0001. Ridgecrest, CA, 1989.

Network Analysis Associates, Inc. *SINDA Manual 1983/ANSI.* Fountain Valley, CA, 1983.

Singh, Dave and John Guy. "Thermal Analysis of PCB Using SINDA at EMPF." *Twelfth Annual Electronics Manufacturing Seminar Proceedings.* Naval Weapons Center, China Lake, CA, 1988. pp. 345-367.

Bibliography

Appendixes

Appendix A
Color Thermal Profiles of Rework Process Simulation

Introduction

In this appendix, color thermal profiles of the solder joint and soldering iron tip at selected intervals of the simulated rework process described in this study are illustrated. The color of nodes in the representations correspond to temperatures in the illustration legends. The initial temperature of the solder joint before heat is applied is 70°F. The temperature at reflow is 361°F, and the temperature range of the soldering iron tip at idle is 689.47 to 695°F. The simulation process lasted 5 seconds.

Description

The initial profile of the tip at idle is shown in Figure A-1. This profile was calculated by running a separate SINDA model of the tip with the same subroutines used in the study to calculate the heat lost by convective cooling of solder joint and tip surfaces. The subroutines used to calculate the heat generated by the heating element of the tip as a function of temperature, also were used in generating the profile.

Figure A-2 shows that at 0.250 second the solder joint (see Figure 6 for an illustration of what is included in the solder joint representation) is heating rapidly, with some nodes (white) already changing from solid to liquid state. It is evident that the lead is promoting the spread of heat in the solder joint by conducting heat down the plated through-hole (PTH). The board material, with a temperature range of 68 to 214.450°F, also is rapidly beginning to heat. The tip at this time (Figure A-3) has cooled considerably, with the temperature at the point of contact with the solder joint at 648°F.

Figure A-4 shows that a 0.500 second the solder is beginning to reflow in the PTH. The temperature of the board, with a range of 104.612 to 287.575°F, continues to rise. The tip (Figure A-5) continues to lose heat, but the temperature of the area of the tip in contact with the solder remains within a few degrees of the reading at 0.250 second, and the heater temperature (left nodal column) drops to 692.235°F. It is evident that the lower part of the tip at the area in contact with the solder joint is cooling faster than the top part. This is because the lower part is in contact with a thicker area of the solder joint, which has a greater thermal load than the thinner area.

Figure A-6 shows that at 0.750 second, only the component side of the solder joint remains solid. But it is beginning to reflow. The board temperature continues to increase, with a range of 141.225 to 324.287°F. The tip temperature overall (Figure A-7) is continually dropping, but the temperature for the area of the tip in contact with the solder joint is relatively stable.

Figure A-8 shows that at 1 second, virtually all the solder has reflowed. Only the outer portion of the solder remains solid. The board temperature is nearing the solder reflow temperature. The tip temperature (Figure A-9) is decreasing, but the rate of decrease is declining. Again, the temperature of the area of the tip in contact with the solder is relatively stable.

Figure A-10 shows that at 1.100 seconds, the solder has completely reflowed and the board temperature continues to rise. The rate of decrease of the overall tip temperature (Figure A-11) has further declined, which indicates that the soldering iron tip will soon begin to recover, or rise.

Figure A-12 shows that at 5 seconds, the solder nodes have reached maximum temperatures for the simulation, with a range of 507.050 to 653.000°F. The range for board temperature is 324.287 to 507.050°F. The tip temperature (Figure A-13) has recovered to 661.823°F at the point of contact with the solder, and the heater temperature has reached 683.941°F.

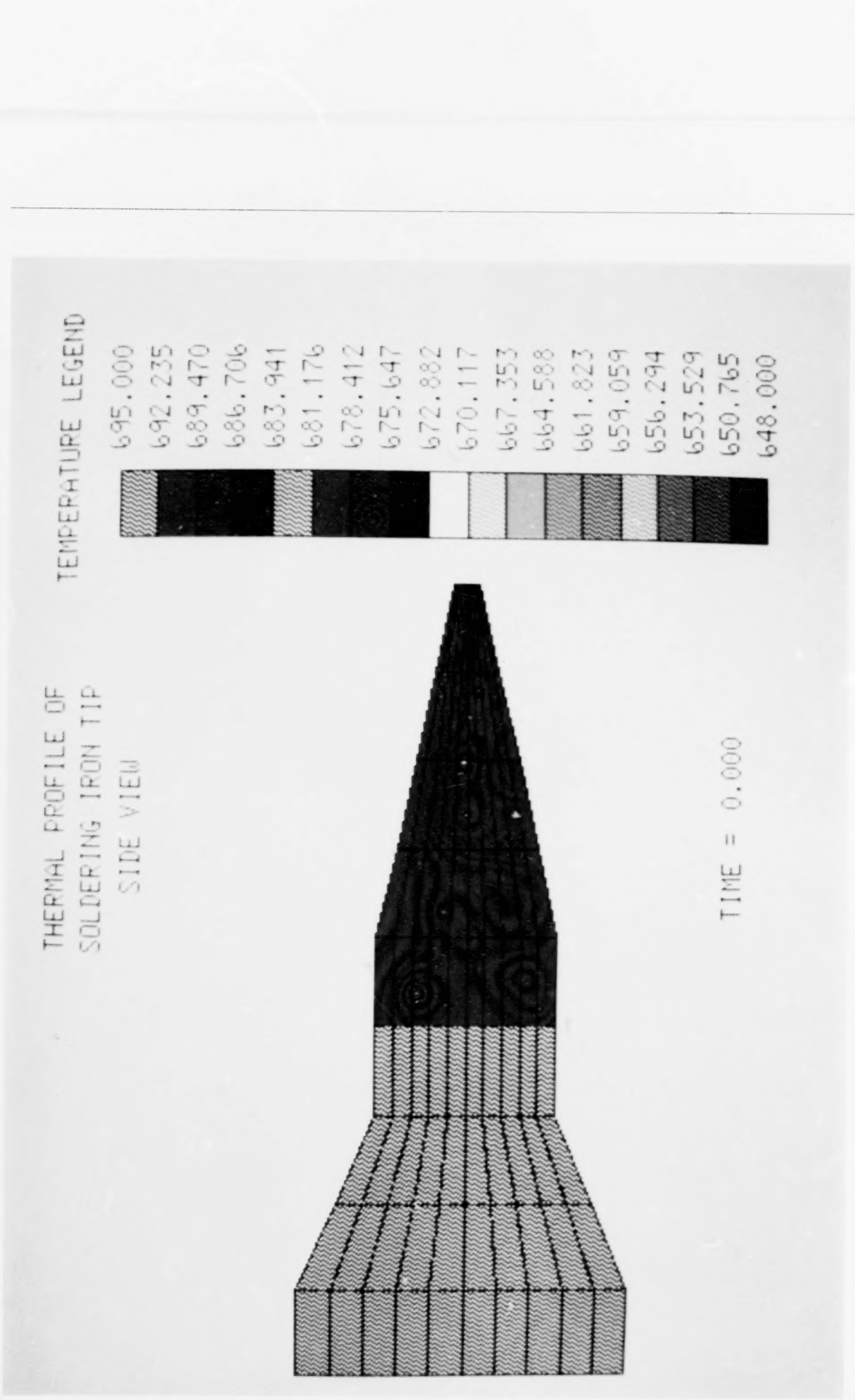

FIGURE A-1. Tip at Idle (Side View).

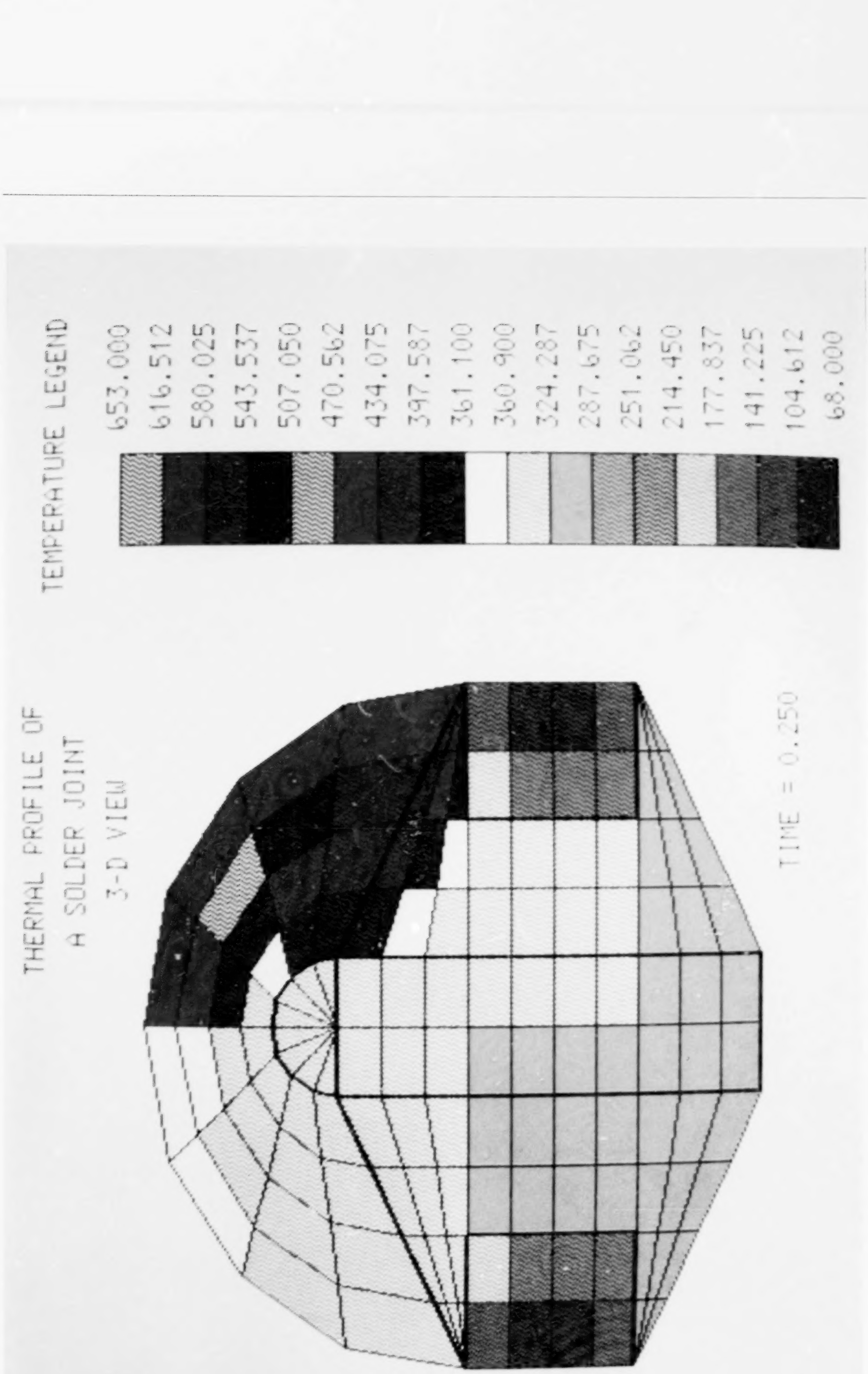

FIGURE A-2. Solder Joint (3-D View) at 0.250 Second.

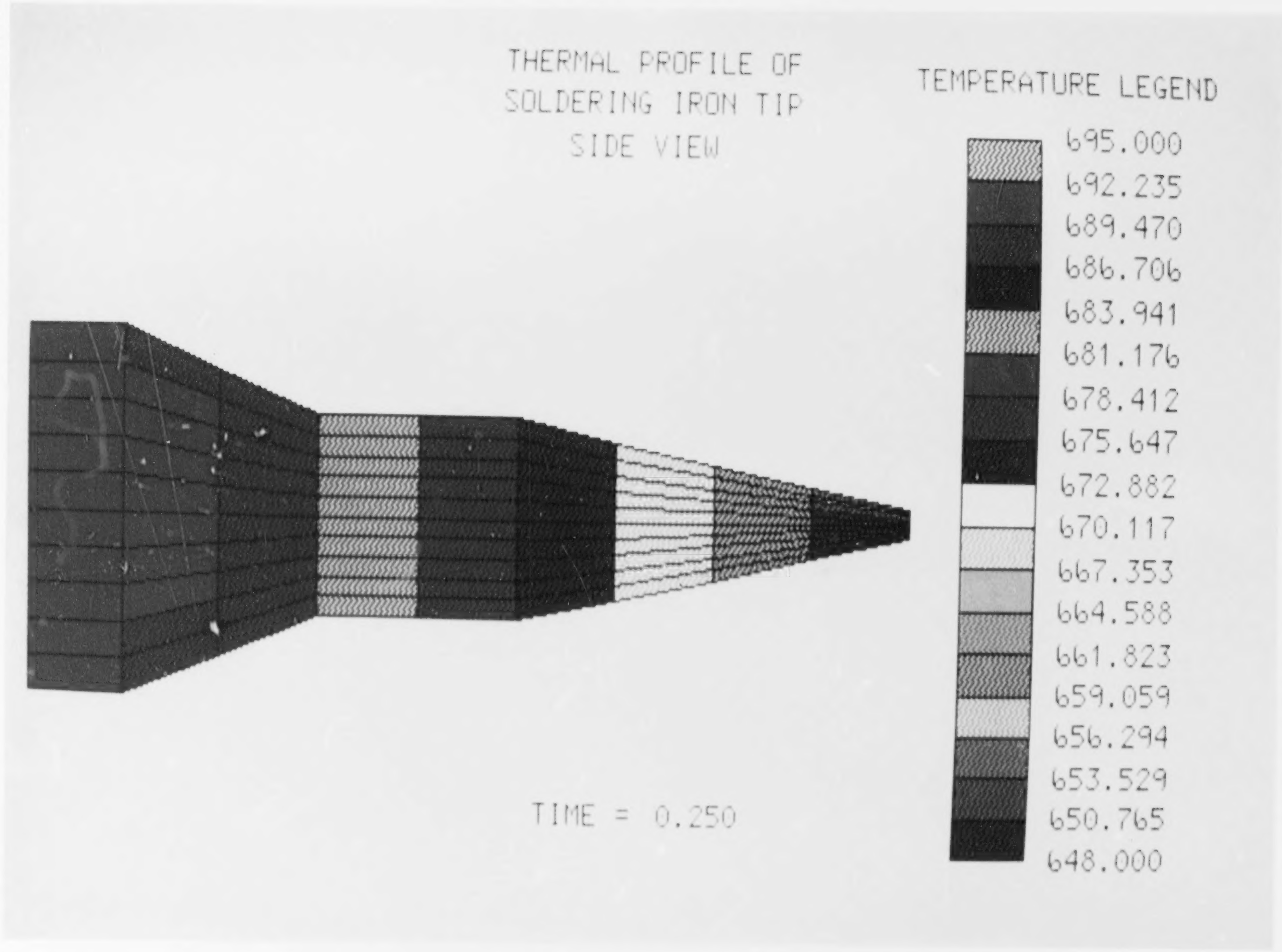

FIGURE A-3. Tip at 0.250 Second.

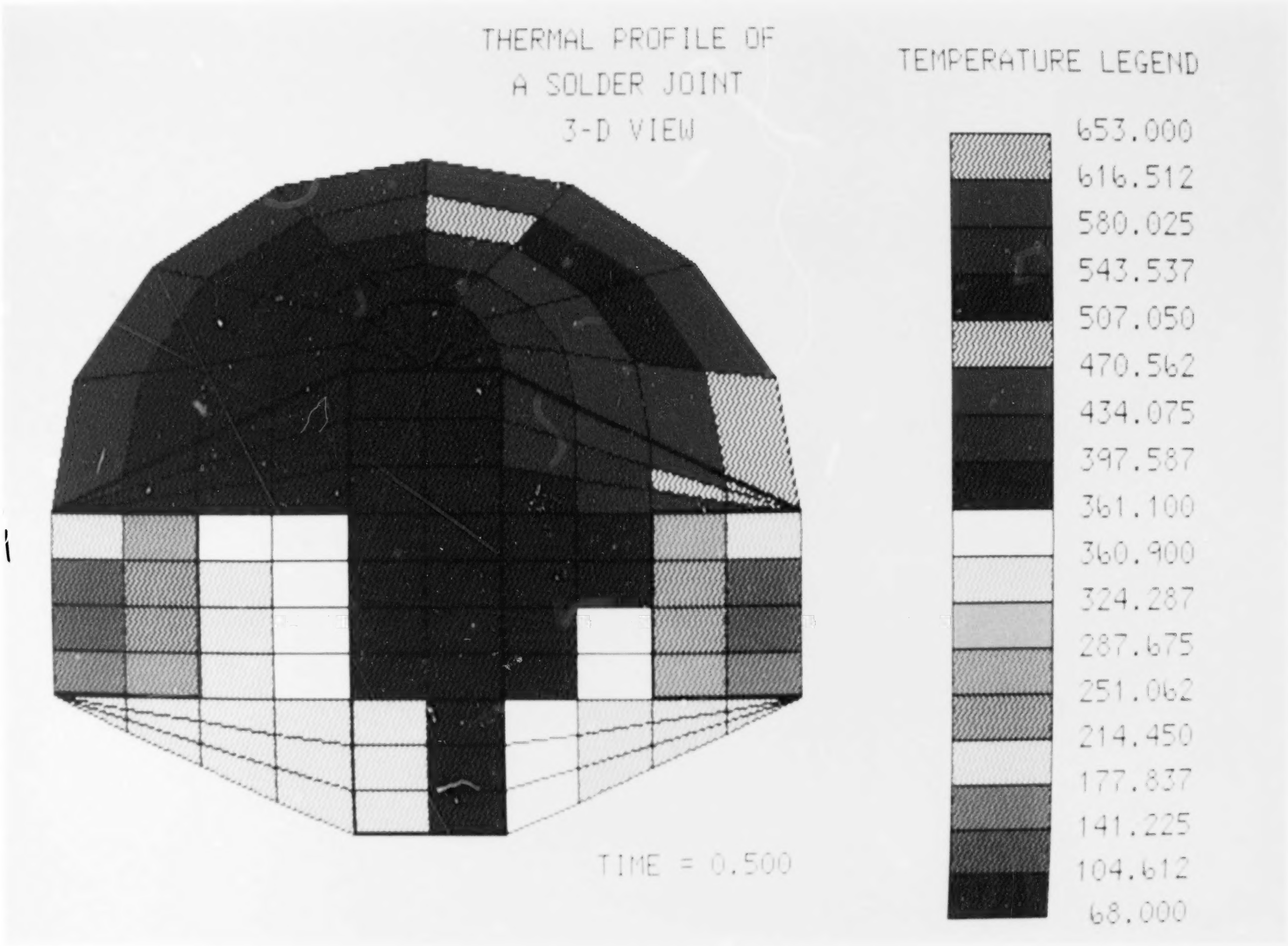

FIGURE A-4. Solder Joint at 0.500 Second.

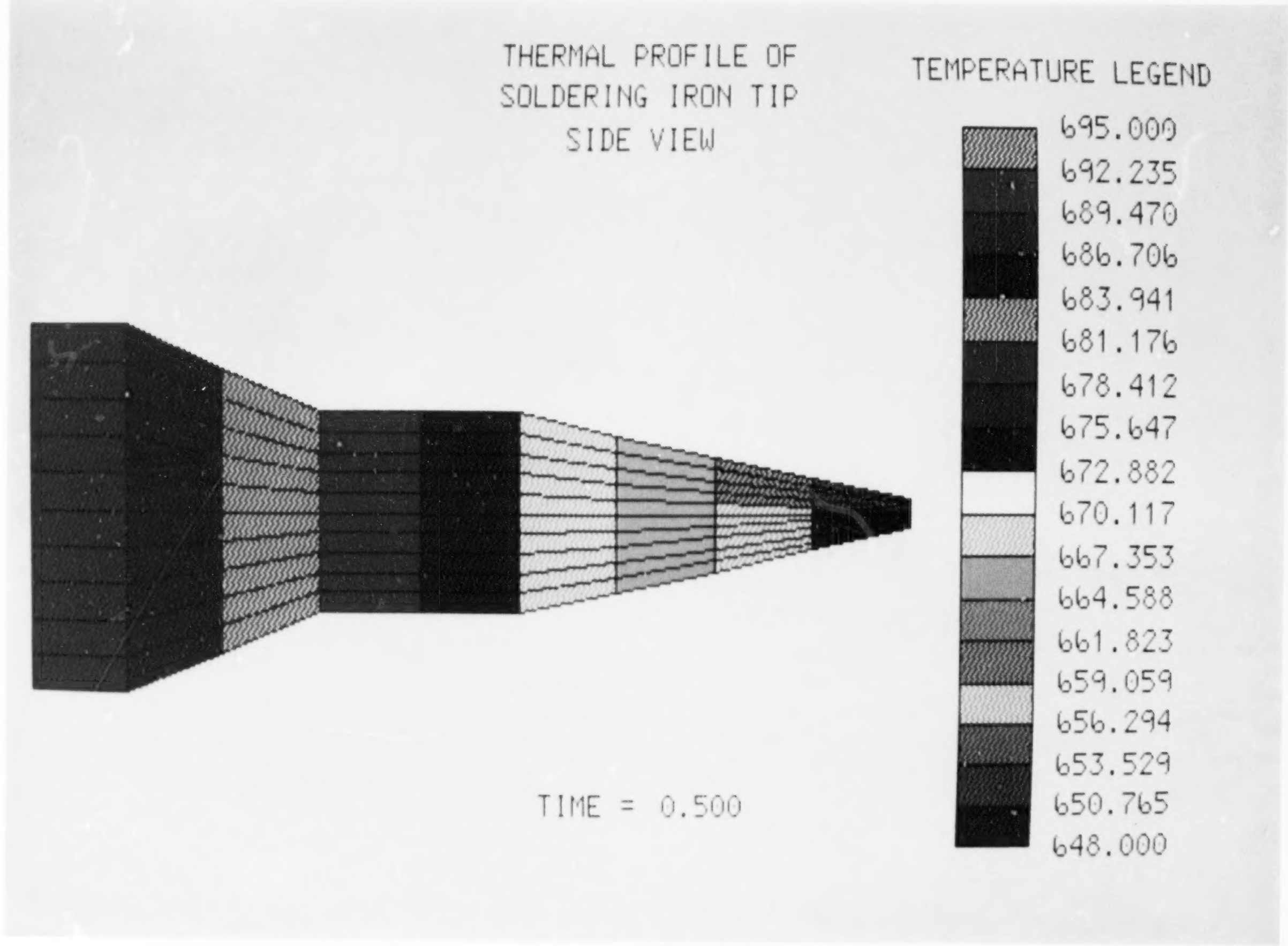

FIGURE A-5. Tip at 0.500 Second.

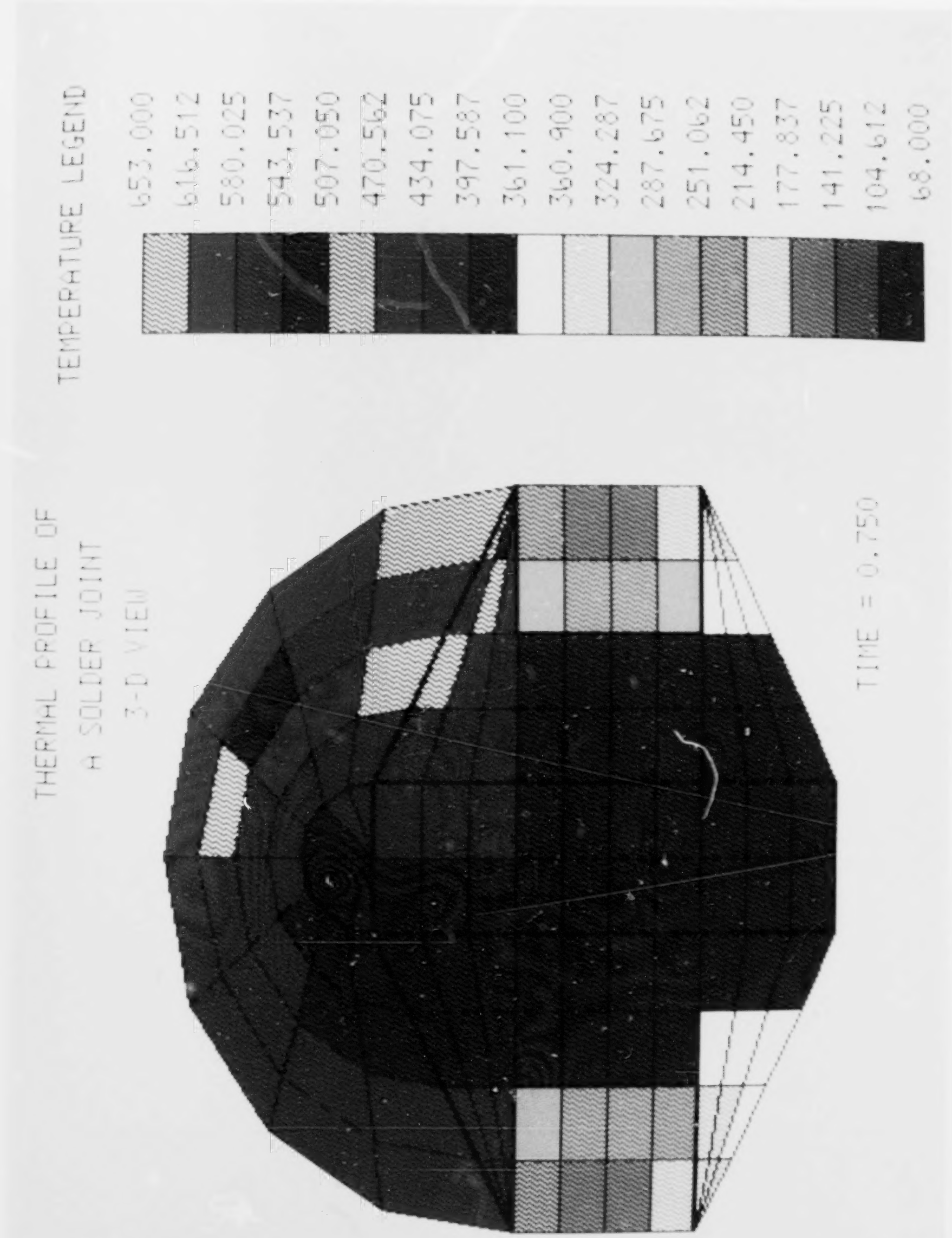

FIGURE A-6. Solder Joint at 0.750 Second.

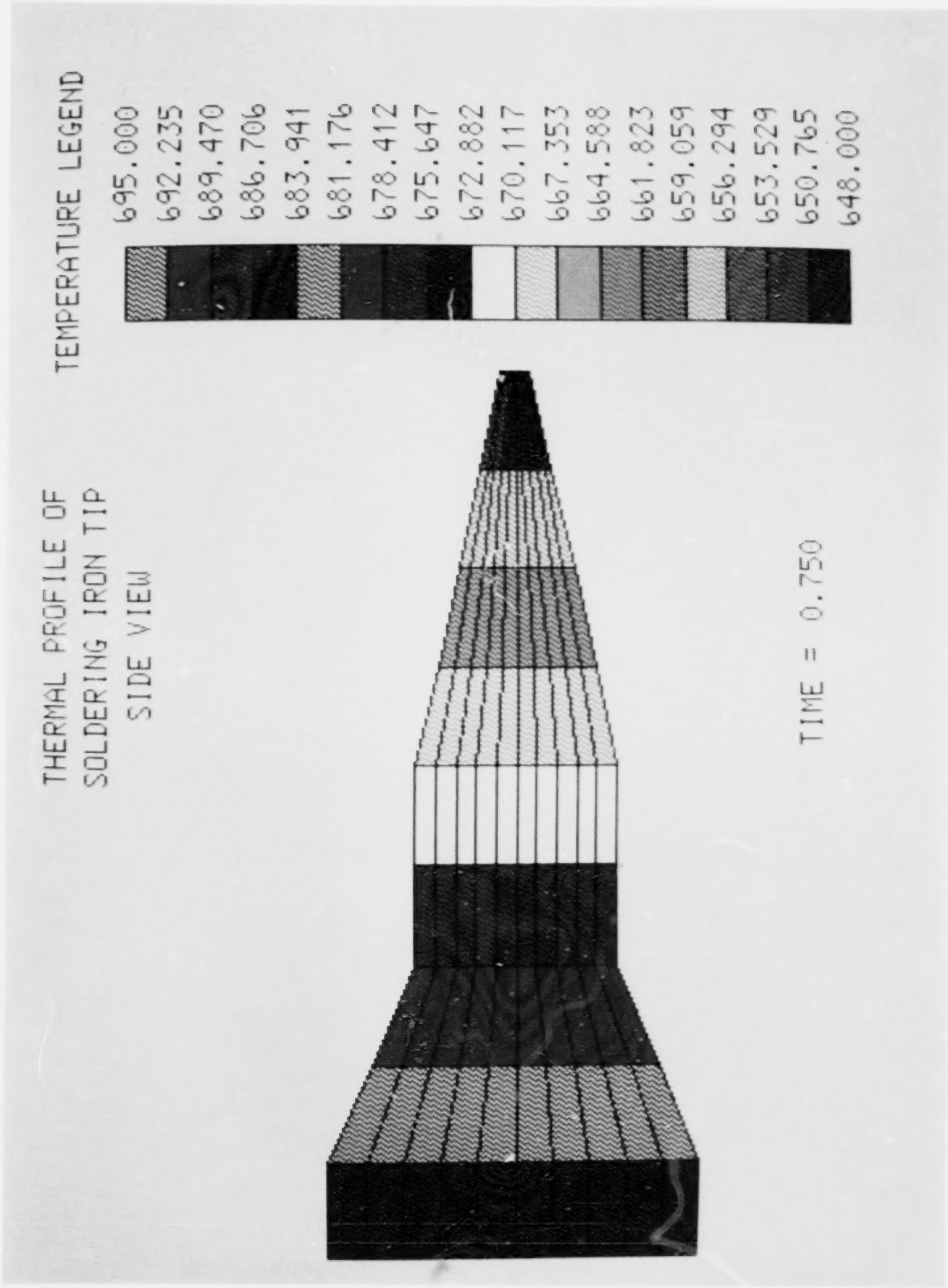

FIGURE A-7. Tip at 0.750 Second.

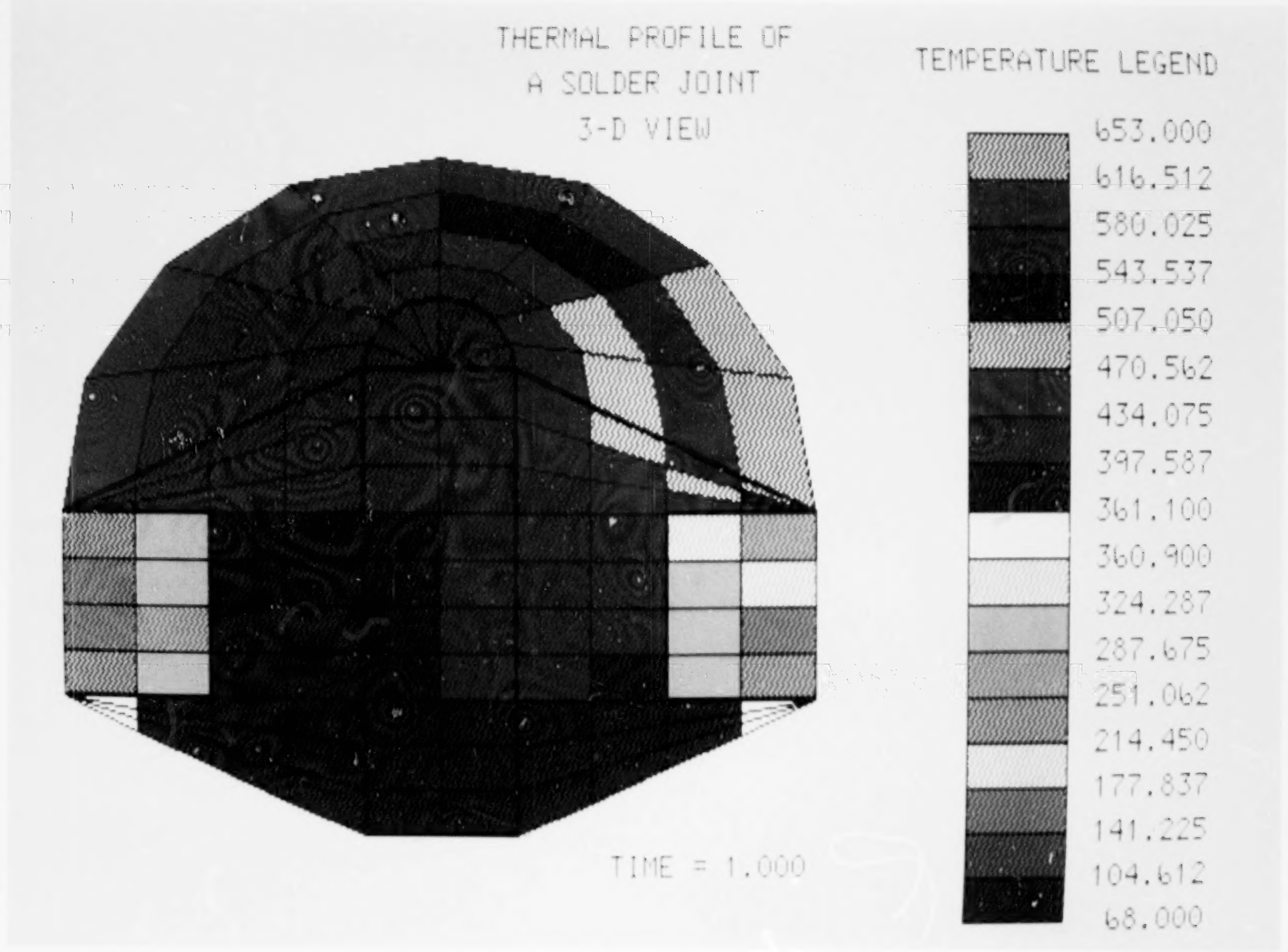

FIGURE A-8. Solder Joint at 1 Second.

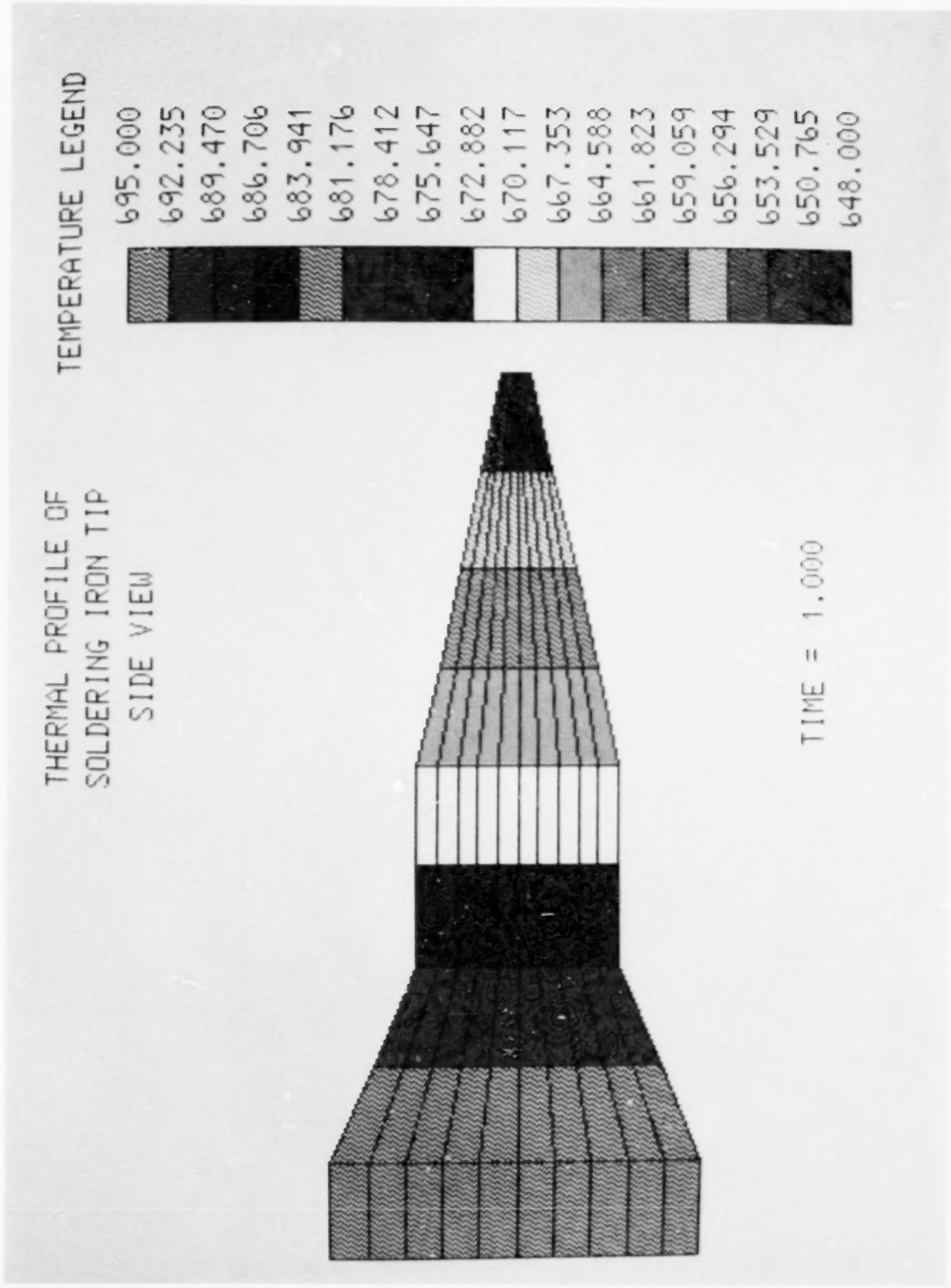

FIGURE A-9. Tip at 1 Second.

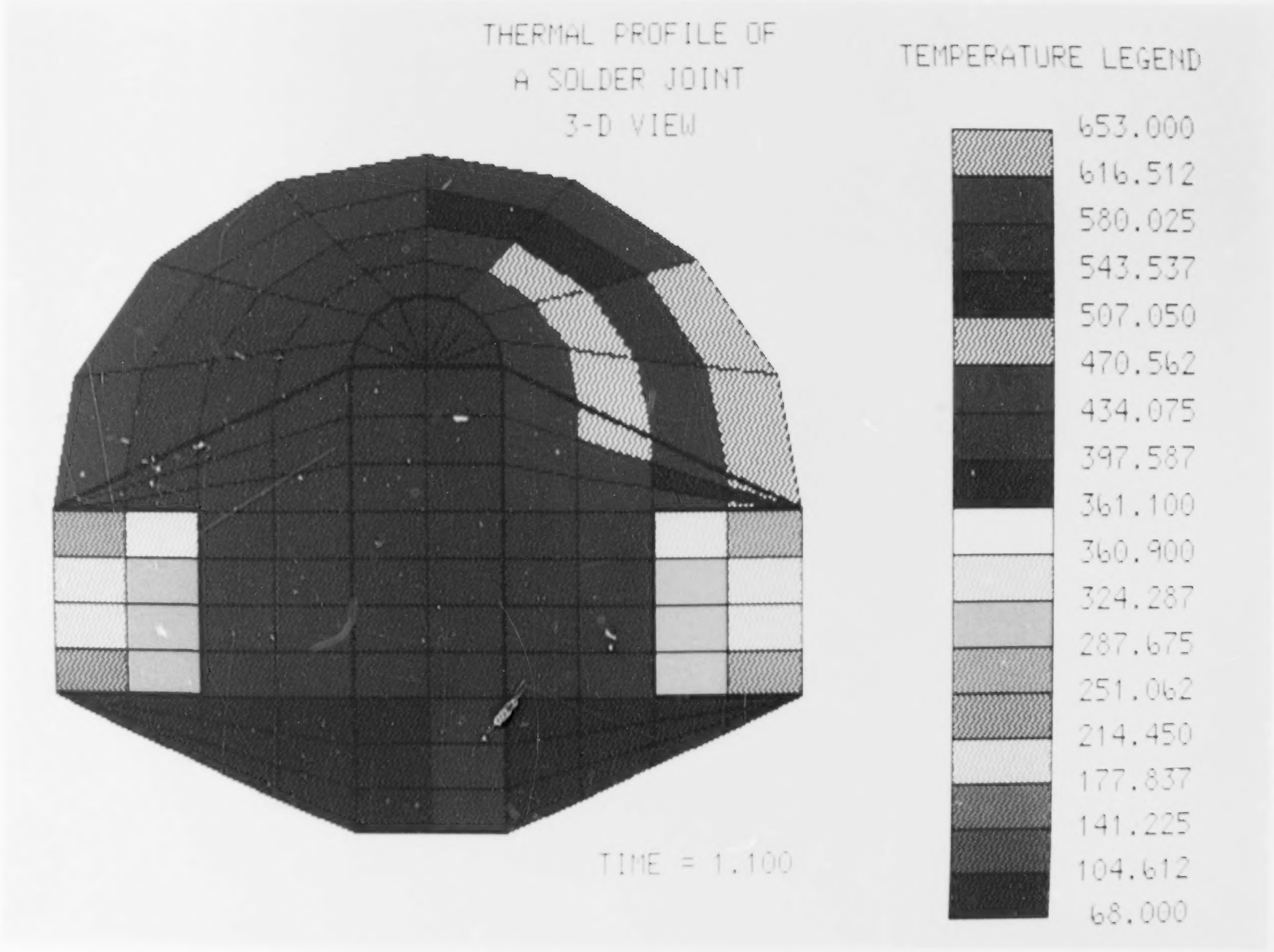

FIGURE A-10. Solder Joint at 1.100 Seconds.

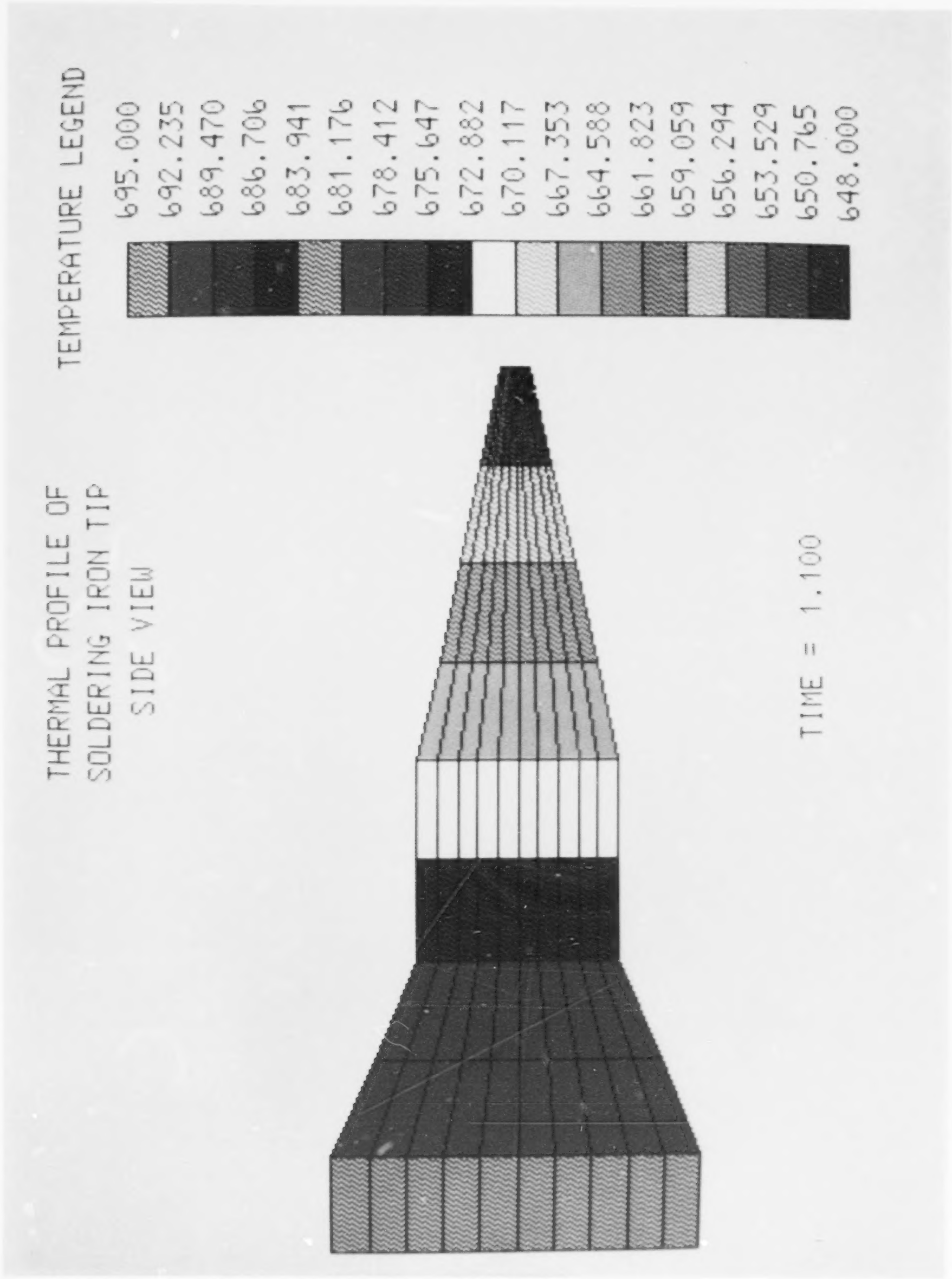

FIGURE A-11. Tip at 1.100 Seconds.

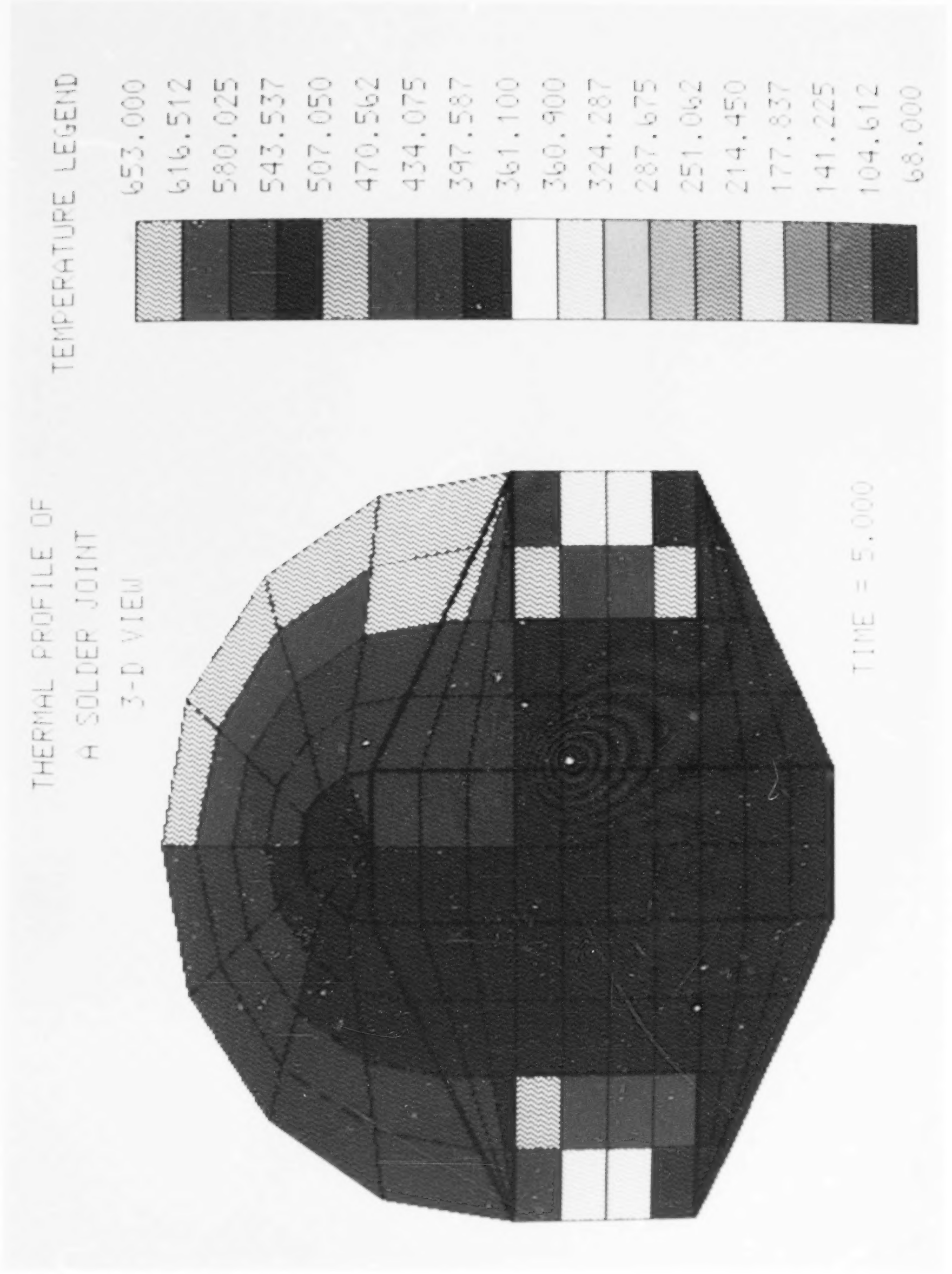

FIGURE A-12. Solder Joint at 5 Seconds.

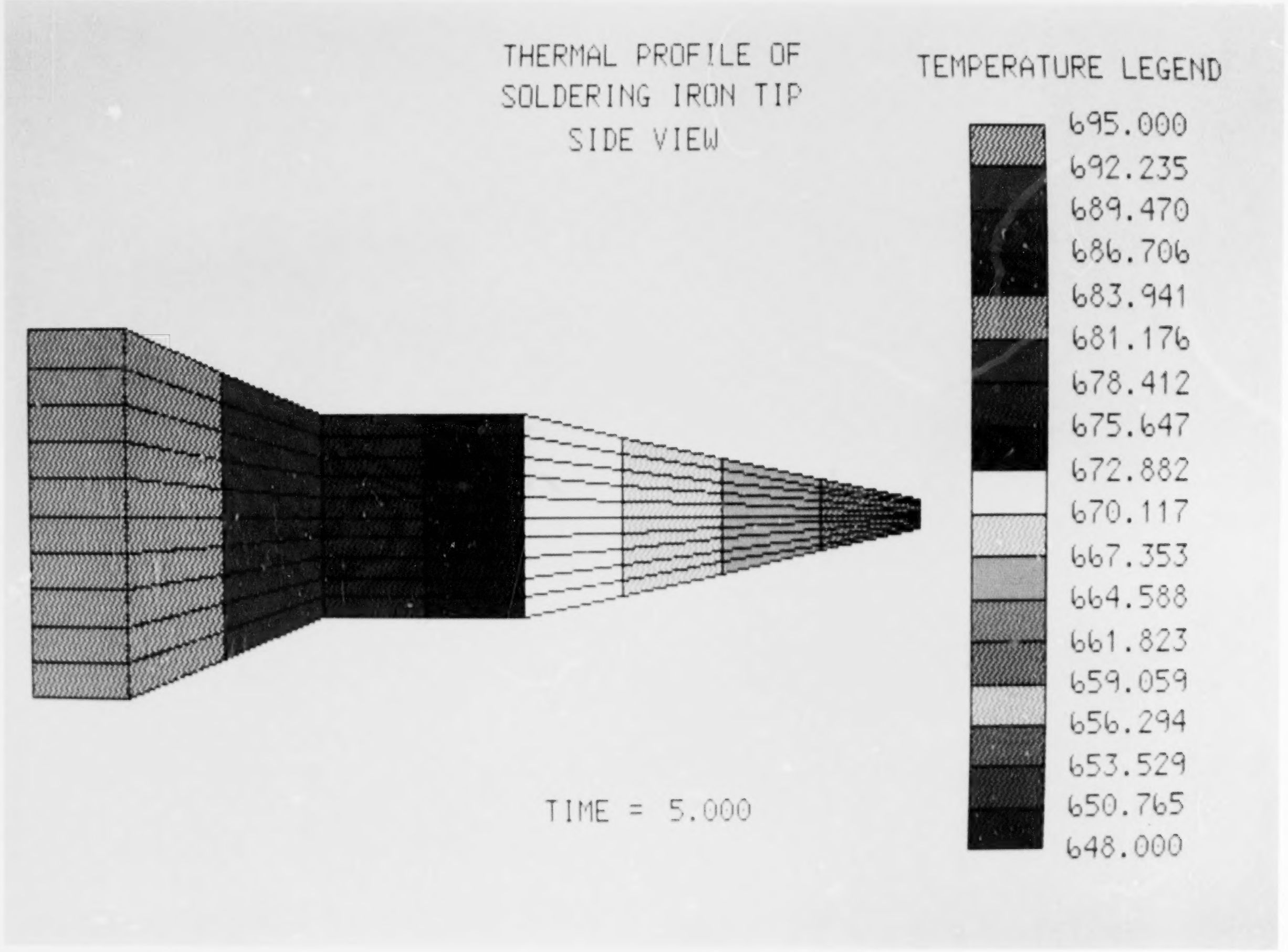

FIGURE A-13. Tip at 5 Seconds.

Summary

During the simulation, the solder reflowed in about 1.1 seconds and reached a maximum temperature of 653°F at 5 seconds. The board material reached 507.050°F, high enough for thermal overstress. The area of the soldering iron tip in contact with the solder held a relatively stable temperature after the initial drop, when it transferred its heat to the solder joint, then began to rise in temperature toward the end of the simulation.

Color Thermal Profiles of Rework Process Simulation

Appendix B
List of Acronyms

AC	Alternating current
EMPF	Electronics Manufacturing Productivity Facility
C-C	Conductor-capacitor
GDDM	Graphic Display Data Manager
PC	Personal computer
PCA	Printed circuit assembly
PCB	Printed circuit board
PTH	Plated through-hole
SINDA	Systems Improved Numerical Differencing Analyzer

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